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INVESTIGATION OF NAPHTHALENE AS A POSSIBLE AIRCRAFT FUEL

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NACA

WASHINGTON

MEMORANDUM REPORT

for

Bureau of Aeronautics, Navy Department

INVESTIGATION OF NAPHTHALENE AS A POSSIBLE AIRCRAFT FUEL

By Dana W. Lee and Alois Krsek, Jr.

SUMMARY

Solid naphthalene was melted and used as fuel in a modified CFR variable-compression engine at a speed of 2000 rpm. Most of the tests were made at a compression ratio of 8 and inlet-air temperatures of 100°, 200°, and 300° F. A series of constant inlet-air pressures was used and the fuel-air ratio was varied through a range as permitted by the engine. The amount of boost used was limited either by the capacity of the laboratory blower system or a condition of rough running which is described. A few tests were made at compression ratios of 9, 10, and 11 and an inlet-air temperature of 100° F.

In order to determine the possibilities of naphthalene as a fuel, the performance was compared to that of a mixture of S-1, a technical grade of isooctane with an octane rating of almost 100, plus 6.0 ml TEL per gallon. Engine conditions were the same as for the naphthalene tests except the inlet-air pressure was boosted to the point of incipient knock over the fuel-air-ratio range.

INTRODUCTION

An investigation of the possibilities of naphthalene as a fuel for use in aircraft engines was requested by the Bureau of Aeronautics, Navy Department.

The history of naphthalene-powered engines dates back to 1907 when the first one was built in Germany. From 1911 to 1914, records indicate that a number of these engines, which were fitted with melting tanks and heating devices to reduce the fuel to its liquid state, were used in Germany and France. Some of the engines used an auxiliary fuel, such as benzol, for starting. The output of the first engines ranged from 4 to 20 horsepower and was later increased to 40 horsepower. Information concerning the performance of naphthalene or conditions of operation is not available although one of these engines had a compression ratio of 6. At that time a good future was predicted for the naphthalene engine when starting difficulties were overcome.

In the present investigation, it was first planned to use naphthalene in the solid state; however, difficulties in pulverizing the material necessitated a change to a fuel system that would permit the use of naphthalene in the liquid state. The fuel system devised for the purpose was successfully used to obtain engine performance data on naphthalene.

These tests were conducted during 1940-1941 at the NACA Langley Field laboratory.

APPARATUS

The engine used was a CFR variable-compression single-cylinder unit with a $3\frac{1}{4}$-inch bore and a $4\frac{1}{2}$-inch stroke fitted with a high-speed crankcase and connected directly to a cradle-type electric dynamometer. The cylinder was of special design, having four openings in the head. Unshrouded sodium-cooled intake and exhaust valves were used. The intake valve opened at 10° A.T.C. and closed at 34° A.B.C.; the exhaust valve opened at 40° B.T.C. and closed at 15° A.T.C.

The air-induction system consisted of a connection to the main air supply line followed by a pressure-control valve, a thin-plate metering orifice, an electric heater tank, and a surge tank. Inlet-air temperature was regulated by means of a bypass around the heater tank, which controlled the mixture of cold and heated air entering the surge tank. Inlet-air temperatures were measured with a thermometer below the surge tank, as shown in figure 1. A mercury manometer connected to the surge tank was used to indicate inlet-air pressures. Another mercury manometer connected ahead of the orifice plate and a differential water manometer connected across the orifice plate were used to determine the weight of air flowing by means of a family of curves computed for the particular orifice diameter used. The intake manifold was made of pipe and flexible-steel hose and provided means for seating and clamping the injection valve in place.

The fuel system was complicated because of the necessity of using the fuel in its molten state. (See fig. 2.) Fuel-supply and fuel-weighing tanks were insulated and provided with heating coils. All fuel lines were covered with a concentric jacket and surrounded with a heating fluid. The need for a jacketed injection pump through which heating fluid could be circulated necessitated a special design of this unit. A standard plunger and sleeve assembly and drive mechanism were incorporated in a housing that contained passages for the heating fluid around the plunger sleeve. A standard injection valve with a pintle nozzle was enclosed within a heavy sheet-brass jacket, as shown in figures 3 and 4.

Dibutyl phthalate, a stable and noncorrosive fluid at high temperatures, was used as the heating medium and circulated through or around the entire fuel system. A diagrammatic layout of the fuel system is shown in figure 1. The flow of heating fluid after leaving the reservoir and heater tank was divided into two circuits with a thermometer placed at each return. It was necessary to maintain the temperature of the returning fluid above 220° F in order to prevent fuel from solidifying at exposed fittings and connections. A combined heating capacity of 8500 watts was required to hold this temperature.

Solid naphthalene in flake or small crystalline form was melted in the upper fuel tank and permitted to flow through a valve at the bottom to both the weighing tank on the scale platform and the injection pump. Flow from the weighing tank to the injection pump was induced by a siphon head of approximately 24 inches. The siphon was started by a rubber bulb attached to a bleeder petcock at the small fuel reservoir within the upper portion of the injection pump. With this arrangement, it was possible to replenish the weighing tank without interruption of the siphon while the engine was running. The fuel-weighing device was similar to the one supplied for CFR engines.

Two spark plugs (Champion BJ-11) with individual ignition coils were used for these tests. One plug was mounted in the rear of the engine between the valve push rods and the other was mounted in a vertical position at the place usually occupied by the bouncing pin. The rear spark plug was connected in parallel with the neon-tube spark position indicator.

A cathode-ray oscillograph with a preamplifier was used at all times to observe knock, preignition, and cyclic variations. A piezoelectric crystal pickup was mounted in the head opening nearest the flywheel. In order to obtain a more sensitive indication of incipient knock, a single differentiating filter was inserted between the oscillograph and the preamplifier, which produced a rate of change of pressure diagram on the screen. This filter consisted of a 0.0002-microfarad coupling condenser between the oscillograph and preamplifier with a 100,000-ohm resistor shunted across the oscillograph vertical input terminals. The action of the filter was to suppress frequencies in the order of engine speed without affecting the high-frequency vibrations caused by incipient or audible knock. In order to maintain frequency synchronization at any engine speed, the horizontal sweep circuit was externally controlled by a rotating contactor mounted on an extension of the distribution shaft.

Ethylene glycol was used as a coolant in the evaporative-type cooling system throughout the investigation; the temperature varied from 315° to 320° F. An electric heater and circulating pump were used to bring the engine head up to operating temperature before starting.

When the engine was operated with a liquid reference fuel, the various heating tanks were replaced with a conventional fuel tank and a weighing stand. Cooling water was circulated through the jacketed injection pump and the jacketed injection valve to prevent vapor lock.

FUELS

The fuels were naphthalene, in a molten state, and a mixture of S-1 plus 6 ml TEL per gallon. The standard CFR reference fuel, S-1, is a technical grade of isooctane with an octane rating of almost 100. The properties of naphthalene and isooctane are listed in the following table:

Fuel	Naphthalene	Isooctane
Formula	$C_{10}H_8$	C_8H_{18}
Molecular weight	128	114
Specific gravity	1.145	.692
Melting point, °F	176	161.1
Boiling point, °F	424.4	210.6
Flash point, °F	184	
Latent heat of fusion, Btu/lb	64.1	
Normal state	Colorless monclinic crystal	Colorless liquid
Net heat of combustion, Btu/lb	16,740	19,150
Theoretical fuel-air mixture	.0769	.0658

$$\text{Ratio of net heat of combustion } \frac{\text{isooctane}}{\text{naphthalene}} = \frac{19,150}{16,740} = 1.144$$

PRELIMINARY TESTS WITH ALPHA METHYLNAPHTHALENE

While the jacketed pump was being built, a series of experiments were made using alpha methylnaphthalene, which is chemically similar to naphthalene but liquid at ordinary temperatures. Alpha methylnaphthalene is used as the zero reference fuel in cetane-number determinations. A 20-percent solution of naphthalene in alpha methylnaphthalene and leaded alpha methylnaphthalene was also used. Most of the experiments were made with no boost but one series was made with a boost of 5 and 10 inches of mercury above atmospheric. In each case, a wide range of fuel-air ratios was covered and the compression ratio raised at each fuel-air ratio until incipient knock began. Readings of power and fuel consumption were taken. The maximum nonknocking compression ratio for alpha methylnaphthalene with no boost was about 8 at a fuel-air ratio of 0.075, about 9 at a fuel-air ratio of 0.100, and about 11 at a fuel-air ratio of 0.130. The addition of 3.0 ml TEL per gallon raised the allowable compression ratio about one-third of a ratio at all fuel-air ratios. The addition of naphthalene to alpha methylnaphthalene lowered the allowable compression ratio about one-half ratio.

A series of check tests made with S-1 fuel at the same engine conditions showed that alpha methylnaphthalene was inferior in all respects to 100-octane fuel. Compression ratios of 1 to 2 higher could be used with S-1 than with unleaded alpha methylnaphthalene, and compression ratios 3 to 3.5 higher could be used with S-1 plus 3.0 ml TEL per gallon than with alpha methylnaphthalene with the same lead addition. Higher indicated mean effective pressures and lower fuel consumptions were obtained with S-1.

All tests with alpha methylnaphthalene were made with inlet-air temperatures of about 310° F in order to prevent excessive dilution of crankcase oil with unvaporized fuel. Dilutions as high as 11.5 percent were measured after 3 hours of operation at an inlet-air temperature of 300° F. When ethylene glycol was substituted for water as the evaporative coolant, however, the dilution after 3 hours was decreased to 3.5 percent. Fouling of the spark plug occurred when the inlet-air temperature dropped below 300° F.

PERFORMANCE TESTS

Molten naphthalene was used at an engine speed of 2000 rpm, compression ratio of 8, inlet-air temperatures of 100°, 200°, and 300° F and at the highest possible inlet-air pressures. No attempt was made to regulate or record mixture temperatures because of the small distance, approximately 1 inch, between the tip of the injection nozzle and the intake port of the engine. A thermometer placed at that point, directly in the fuel spray, would not have given a true indication of mixture temperature. With the inlet air at 100° and 200° F, maximum performance of the fuel was not attained due to insufficient capacity of the laboratory blower system. At the time the naphthalene tests were made, the maximum air pressure available at the engine intake port was about 57 inches of mercury absolute. Tests were made with this inlet pressure and with inlet-air temperatures of 100° and 200° F over a fuel-air-ratio range as permitted by the engine. The leanest mixture was the one at which the engine still operated smoothly and the richest mixture was the one used just before the spark plugs fouled.

With an inlet-air temperature of 300° F, the run was made at a constant inlet-air pressure of 42.0 inches of mercury absolute over the fuel-air-ratio range. The pressure in this case was limited by a condition of rough running, which began without warning at higher inlet pressures and threatened to damage seriously the engine. In order to determine the maximum constant inlet-air pressure that could be safely used, the fuel-air ratio was adjusted for maximum power while the inlet pressure was increased to the point of rough running. In this manner the condition was encountered only once over the fuel-air-ratio range. No attempt was made to use a higher air pressure in the lean or rich mixture region.

The extremely rough running as experienced during the naphthalene tests did not give the usual indications of knock. It occurred for intervals of several cycles as a violent thumping or pounding within the engine and gave the impression that the engine was rapidly accelerating. This condition began without warning and usually stopped before any change in engine operation could be made. The oscillograph screen indicated very high pressures and changes of pressure of greater magnitude than are usually caused by knock. The common ringing ping of audible knock, as encountered with gasolines and also with naphthalene at advanced spark settings incident to the determination of the optimum advance angle, did not occur. No tests for preignition were made during severe thumping as the fuel supply was shut off to prevent damage to the engine. When the ignition switch was opened immediately after the thumping stopped, no signs of preignition were evident.

During the investigation one engine failure was caused by rough running. The sleeve in which the cylinder was mounted for the purpose of raising and lowering the head was cracked. Conditions preceding the failure were: speed, 2000 rpm; compression ratio, 9; spark advance, $20\frac{1}{2}^\circ$ B.T.C.; inlet-air temperature, 146° F; inlet-air pressure, 53 inches mercury absolute; indicated mean effective pressure, 241.5 pounds per square inch; and fuel-air ratio, 0.081. From this point the mixture was enriched by a small addition of fuel. A falling off of power output was noticed, possibly due to one spark plug cutting out. After 4 or 5 seconds, the ignition trouble apparently corrected itself and the engine immediately went into violent rough running and failed before it could be stopped.

The spark-advance angle, employed in the tests for each compression ratio, was obtained by plotting indicated power output against spark advance with the engine operating at atmospheric inlet pressure, inlet-air temperature of 100° F, and optimum fuel-air ratio. The spark-advance angle used was the angle that produced a reduction of 1 percent of maximum indicated power on the retarded side of the curve. As the peak of such a spark curve is almost flat, it is difficult to pick the optimum spark-advance angle. Operation with a slightly retarded spark permitted additional boost and the engine was penalized less than if the spark was too far advanced.

Fuel-injection timing was 40° A.T.C. on the intake stroke and the valve opening pressure was 350 pounds per square inch. These two conditions remained constant for all tests described in this report.

In order to compare the performance of naphthalene with a known fuel, a mixture of S-1 and tetraethyl lead was used. Preliminary testing with increasing amounts of lead showed that S-1 plus 6 ml TEL per gallon approached the performance of naphthalene. This mixture was used because the addition of more lead would not have greatly increased the knock limit of the mixture. During the tests of S-1 plus lead, maximum allowable inlet-air pressure was used over the fuel-air-ratio range and with this exception all other conditions were the same as for the corresponding naphthalene tests.

The results of the tests with naphthalene and leaded S-1 for the same inlet-air temperature are plotted together for easier comparison. Figures 5, 6, and 7 show the results for inlet-air temperatures of 100°, 200°, and 300° F, respectively. The naphthalene curves are reproduced as a group in figure 8; leaded S-1 curves are reproduced as a group in figure 9.

Additional naphthalene tests at an engine speed of 2000 rpm were made with atmospheric inlet pressure. The results with inlet-air temperatures of 100°, 200°, and 300° F and with compression ratio of 8 are shown in figure 10. The effects of varying the compression ratio from 8 to 11 with atmospheric inlet pressure and constant inlet temperature of 100° F are shown in figure 11.

The barometric pressures recorded during the period of these tests varied from 29.75 to 30.4 inches of mercury.

SUPPLEMENT

An attempt was made to operate the engine with solid fuel. It was observed during the tests that when molten naphthalene was discharged into the atmosphere by the injection valve a cloud of fine white naphthalene dust formed several inches from the end of the valve. An intake manifold was made, which consisted of a vertical steel cylinder of 5-inch inside diameter and 18 inches long with a seat for the injection valve on the top cover. Inlet air entered at the top and was passed around the end of the injection valve in order to carry the solid particles of fuel into the engine. Attempts to start the engine at various speeds, compression ratios, and fuel quantities were unsuccessful.

Another problem investigated during the naphthalene tests was the possibility of starting a cold engine using molten fuel and cold inlet air. The inlet air and engine temperatures were both about 80° F and the fuel temperature was in the usual temperature range of 220° to 230° F. With the engine motoring and the ignition switch on, the fuel was injected into the manifold. The engine did not fire and after about 1 minute it was noticed that the flow of inlet air had almost stopped. When the intake manifold was removed, it was found that the fuel, after coming into contact with the cold intake port walls, had solidified and almost completely filled the port, as shown by the photograph in figure 4. After the solid naphthalene was removed from the intake port, attempts to fire the engine were made while the coolant temperature was being increased. It was not until the coolant temperature reached 215° F that the engine did fire. Evidently the engine temperature had to exceed substantially the naphthalene melting point for ready starting.

Fouling of spark plugs was a frequent cause of trouble during the tests. It was necessary to clean the plugs before each run and often during a run. The Champion RJ-11, a cold running plug, was used to avoid the preignition tendencies of warmer running plugs, although it is more susceptible to fouling. Engine performance was limited by preignition when a B. G. 3B-2 spark plug was used.

The largest source of trouble and cause of delay was in the injection pump, the pump plunger and plunger sleeve being lapped to fit within very close limits in order to prevent leakage of fuel around the plunger. Normally these parts operate at or near atmospheric temperature and even with nonlubricating fuels, such as gasoline, give long service. It is believed that the high temperature of the fuel caused the surfaces to gall and freeze the plunger within the sleeve. A special plunger and sleeve assembly with a looser fit was obtained and gave less trouble than standard parts.

Another observation made during these tests was the amount of dilution of crankcase oil with naphthalene. Analysis of the crankcase oil after various periods of running gave the following results: after 1.25 hours at an inlet-air temperature of 240° F, dilution 1.5 percent by weight; 2.5 hours at 280° F, 1.7 percent; 2.66 hours at 100° F, 2.6 percent; 25 hours at various inlet-air temperatures from 100° to 250° F, 7.4 percent.

ANALYSIS OF DATA

When the curves in figures 5 to 7 were studied from a standpoint of fuel consumption, it appears that, for fuel-air ratio larger than about 0.77, naphthalene is a much better fuel than leaded S-1. The explanation for the intersection of the consumption curves lies in the greater fuel-air ratios required with naphthalene for the complete utilization of the oxygen.

For naphthalene, the stoichiometric mixture ratio is 0.0769, whereas for isooctane it is 0.0658. The fuel-air ratios determined were divided by the stoichiometric ratios and the data were replotted as shown in figures 12 to 14. When plotted in this manner, any vertical displacement of the curves is due to differences in the lower heating value or thermal efficiency of the fuels in the engine.

The following table, prepared from the data presented in figures 12 to 14, shows that in the rich region the ratio of fuel-consumption rates, naphthalene to isooctane, is about the same as the ratio of the net heat of combustion of the two fuels (1.144).

Fuel-air ratio / Stoichiometric ratio	Fuel consumption (lb/ihp - hr) 0.8	1.0	1.2
Inlet-air temperature, 100° F			
S-1 + 6 ml TEL	0.346	0.390	0.480
Naphthalene	.472	.468	.536
Ratio, naphthalene to S-1	1.364	1.200	1.116
Inlet-air temperature, 200° F			
S-1 + 6 ml TEL	0.351	0.378	0.472
Naphthalene	.440	.461	.538
Ratio, naphthalene to S-1	1.254	1.219	1.140
Inlet-air temperature, 300° F			
S-1 + 6 ml TEL	0.355	0.380	0.464
Naphthalene	.428	.459	.534
Ratio, naphthalene to S-1	1.205	1.208	1.151

This fact indicates that both fuels in the rich region have the same thermal efficiency in the CFR engine. In the lean region the thermal efficiency for naphthalene was lower with a definite improvement as the inlet-air temperature was raised, possibly due to better vaporization of the fuel in warmer air.

From a comparison of indicated mean effective pressure, naphthalene has a higher knock limit than S-1 plus 6 ml TEL per gallon. Figure 5 does not show a great advantage of naphthalene in this respect because its maximum performance was not attained. The superiority of naphthalene becomes more apparent in figures 6 and 7.

Figures 10 and 11 show the effects of varying the inlet-air temperature and compression ratio with other conditions remaining constant. Higher inlet-air temperatures cause a decrease in indicated mean effective pressure and higher compression ratios result in lower fuel-consumption rates and increased indicated mean effective pressure.

CONCLUSION

The data obtained from an investigation of naphthalene as a possible aircraft fuel indicate that:

1. Naphthalene has a higher knock limit and is capable of higher indicated mean effective pressures than a mixture of S-1 plus 6 ml TEL per gallon.

2. The specific fuel consumption of naphthalene is higher than that of S-1 because of its lower heating value. In the rich-mixture region, naphthalene has about the same thermal efficiency as S-1. In the lean-mixture region, the thermal efficiency of naphthalene is lower than that of S-1 and increases with increasing inlet-air temperatures.

3. Because naphthalene is solid at ordinary temperatures, some auxiliary equipment for starting will probably be needed.

4. Unless rather high engine temperatures are employed, crankcase dilution may be a serious difficulty. At low temperatures some solid separation may clog the oil lines.

National Advisory Committee for Aeronautics,
Langley Memorial Aeronautical Laboratory,
Langley Field, Va., August 28, 1941.

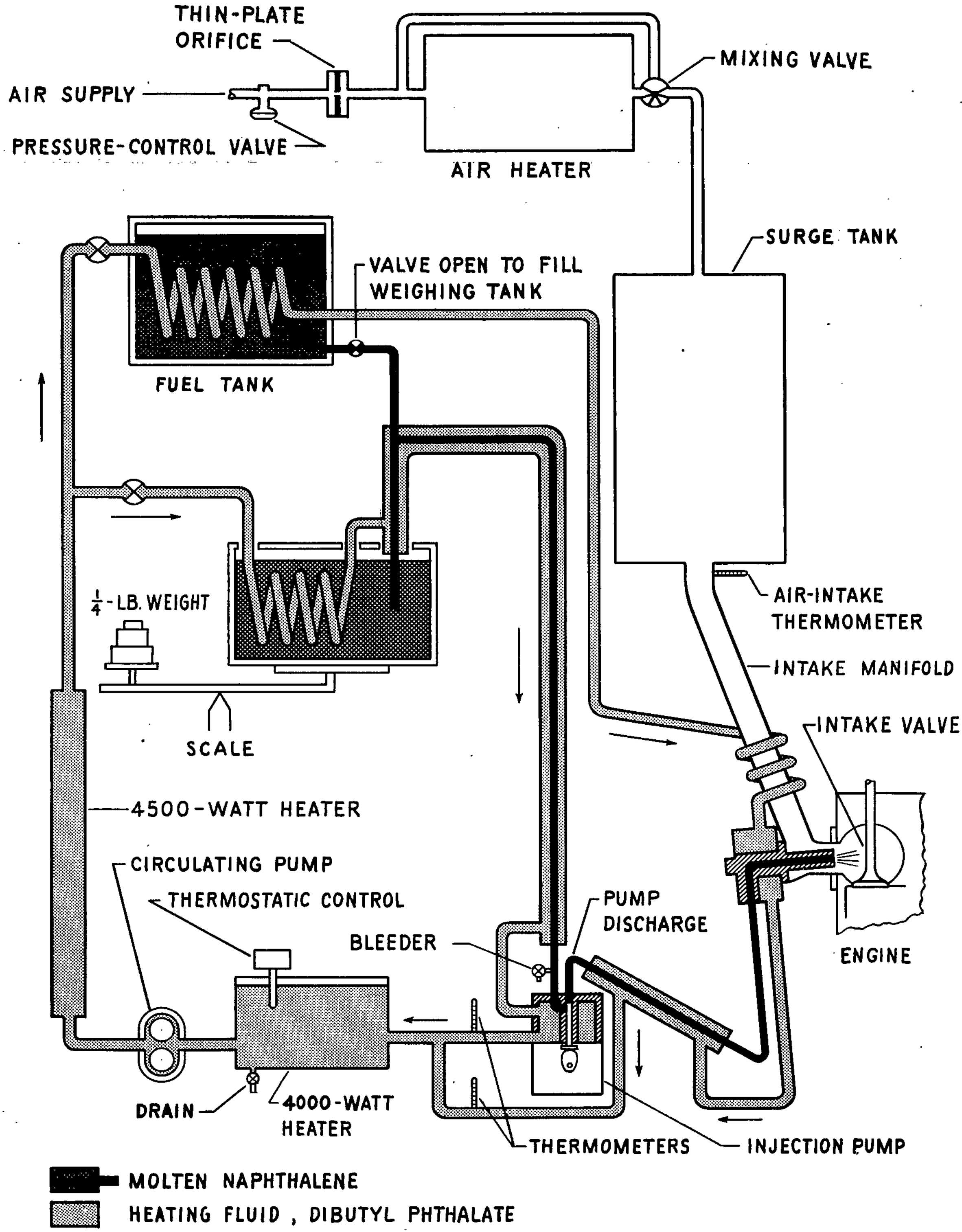

FIG. I DIAGRAMMATIC LAYOUT OF NAPTHALENE SYSTEM

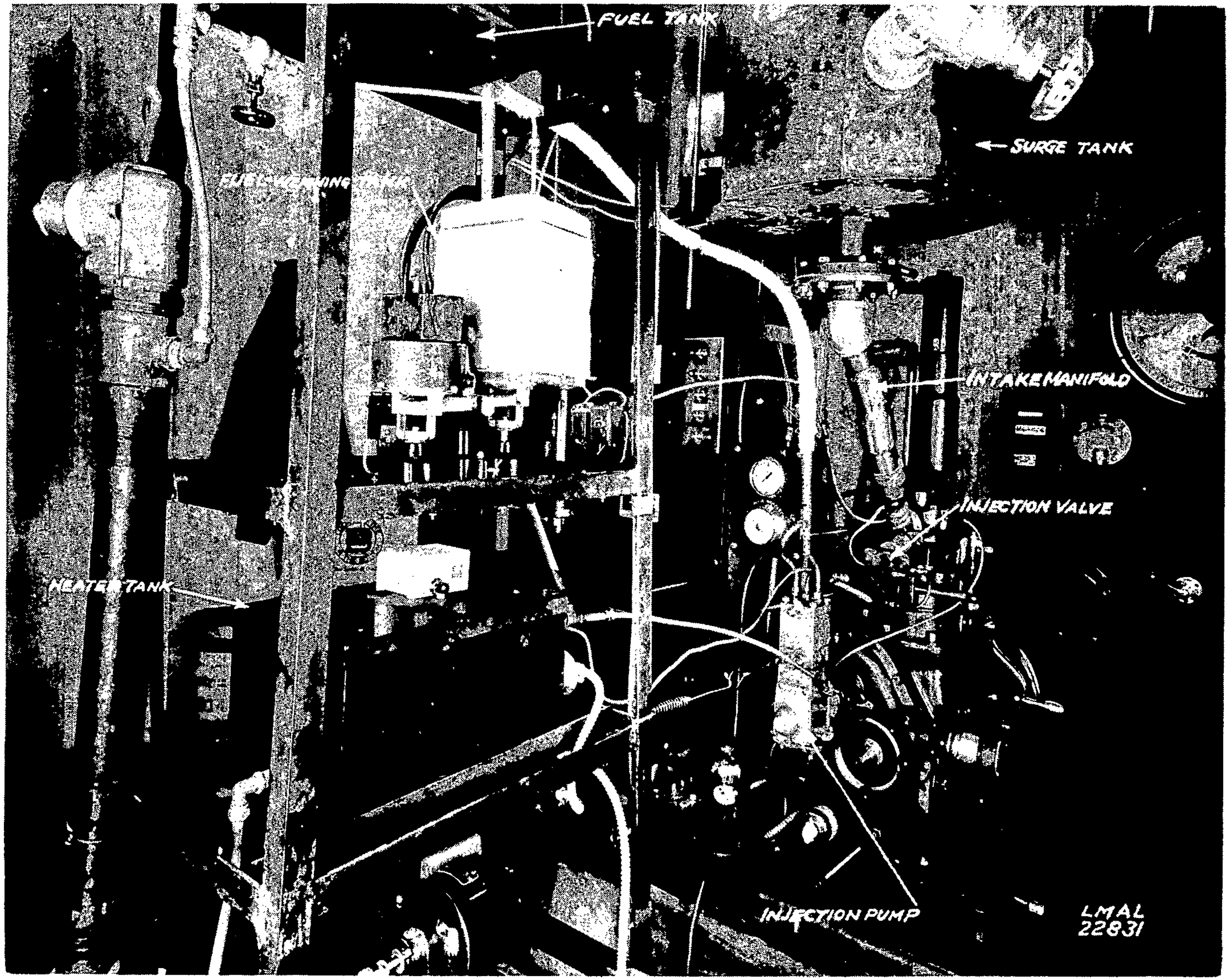

Figure 2. - View of complete naphthalene fuel system and engine.

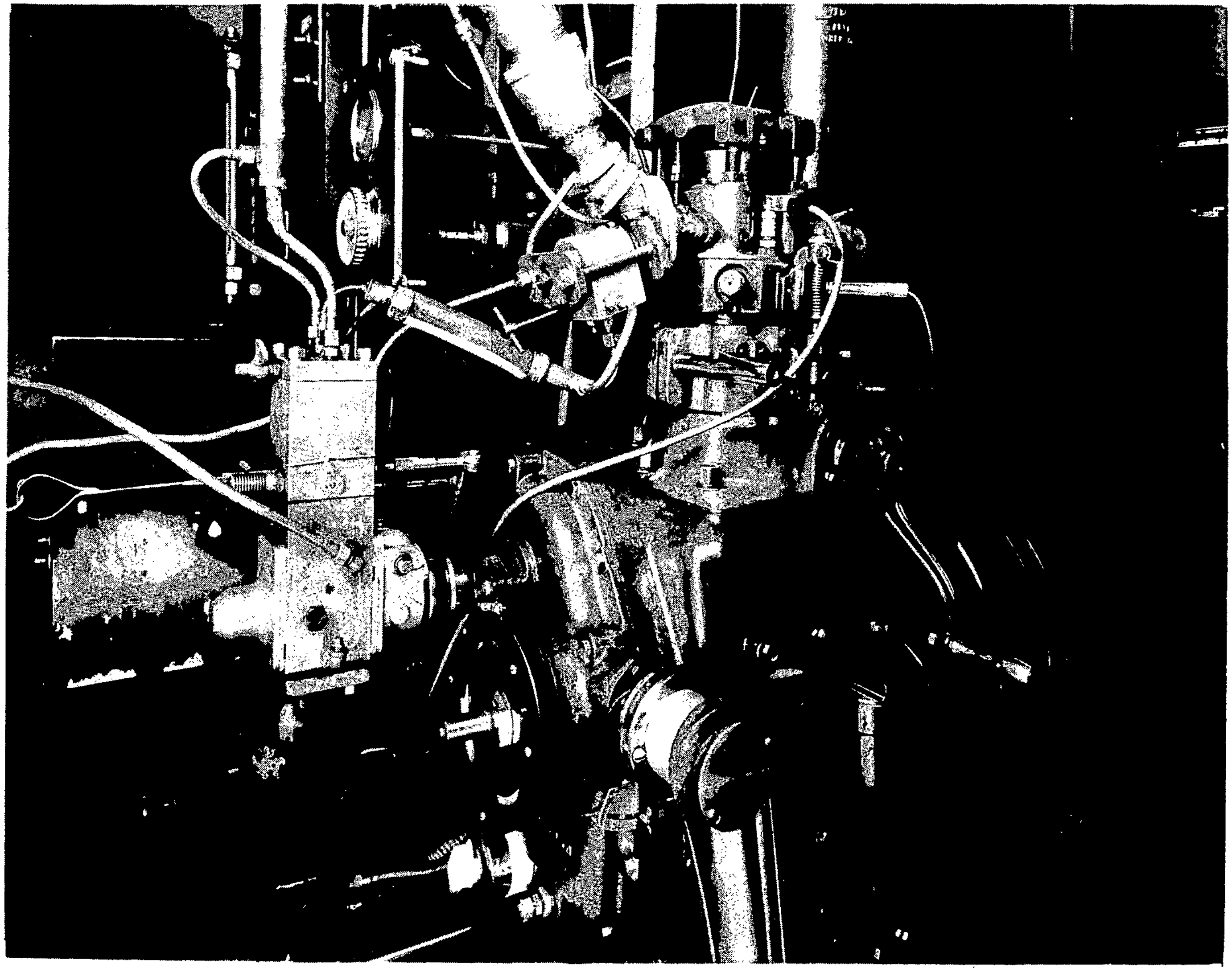

Figure 3. - View of injection pump, injection valve, and engine.

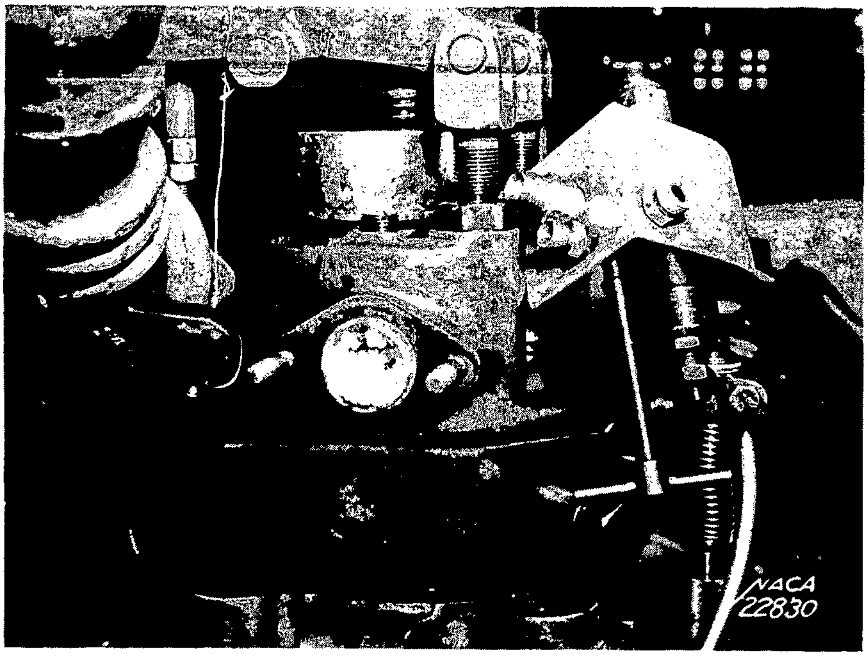

Figure 4. - Choking of intake port caused by solidification of molten fuel during an attempt to start a cold engine. Portion of intake manifold shown at left and jacketed injection valve at right.

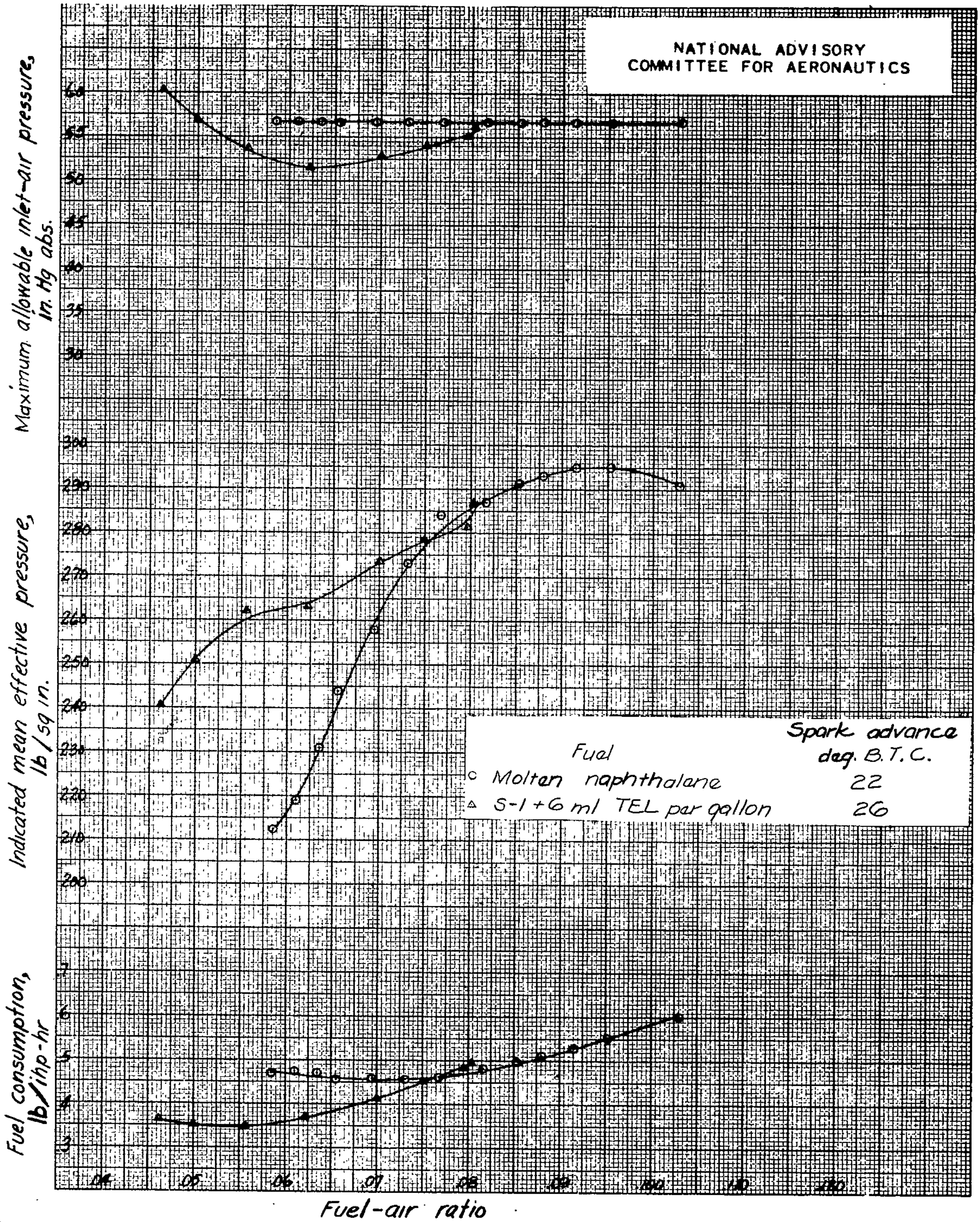

Figure 5. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 100° F; compression ratio, 8; engine speed, 2000 rpm; maximum inlet-air pressure available during naphthalene tests, 56.75 inches mercury absolute.

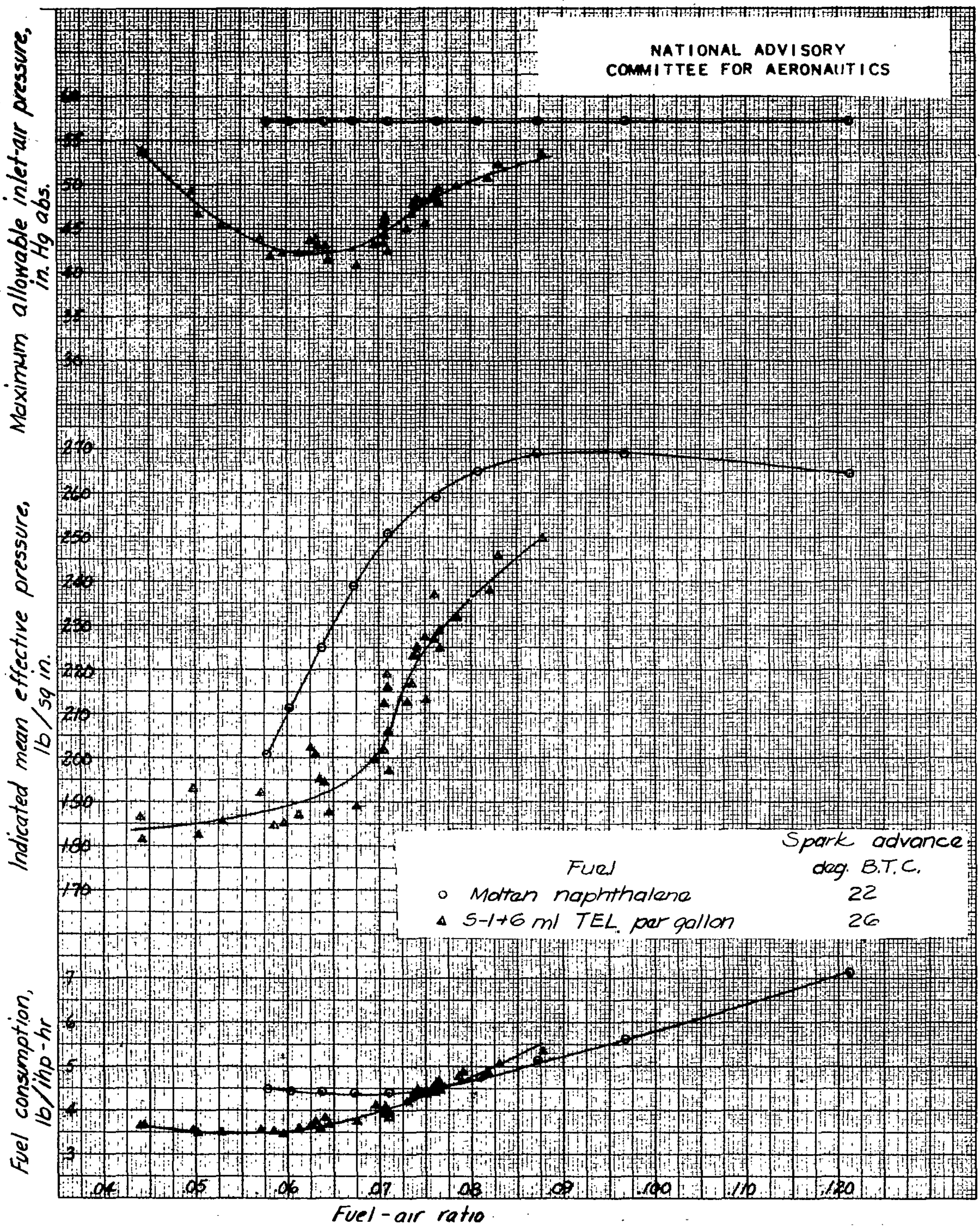

Figure 6. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 200° F; compression ratio, 8; engine speed, 2000 rpm; maximum inlet-air pressure available during naphthalene tests, 57.2 inches mercury absolute.

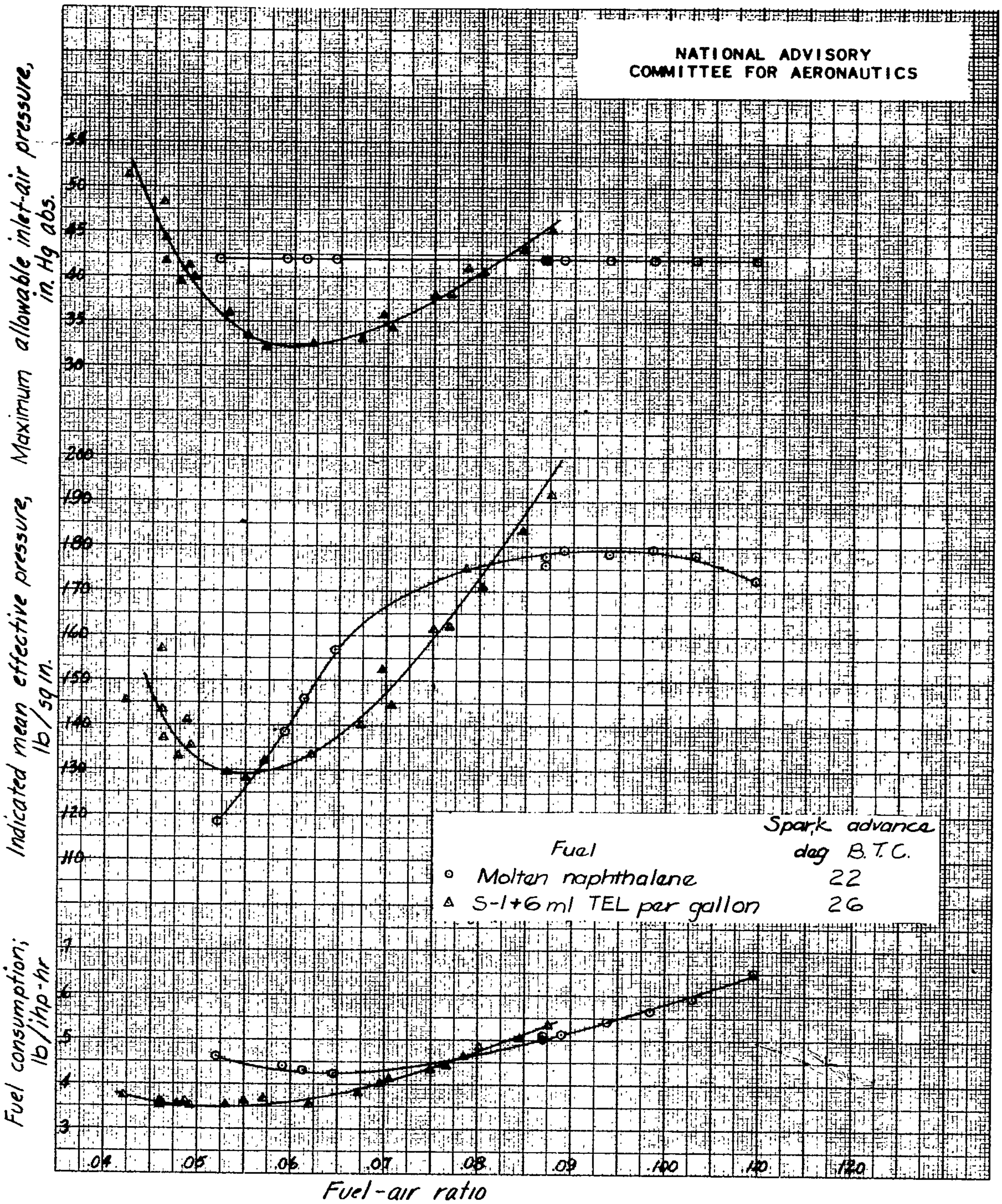

Figure 7. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 300° F; compression ratio, 8; engine speed, 2000 rpm; maximum safe inlet-air pressure during naphthalene tests, 42.0 inches mercury absolute.

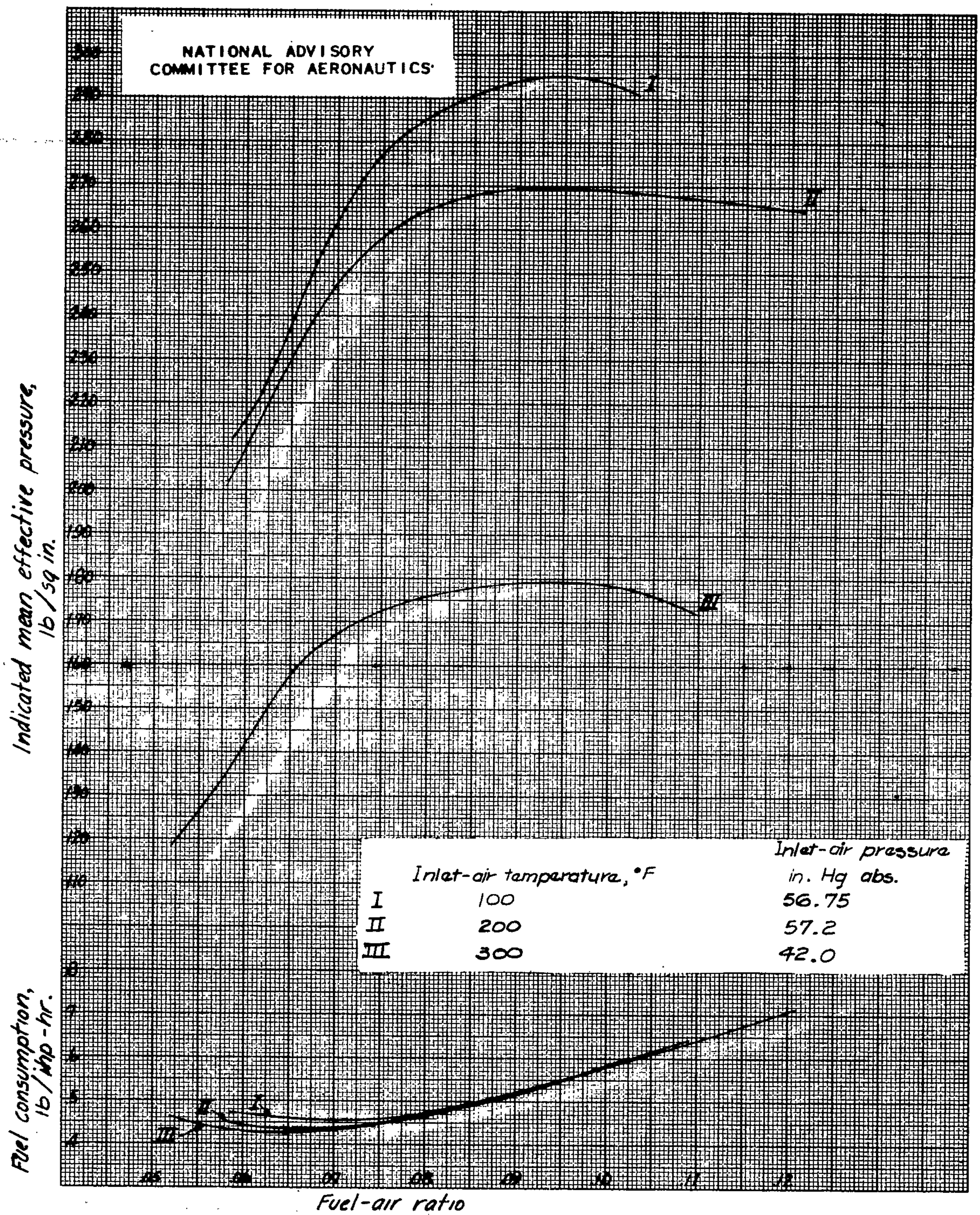

Figure 8. - Effect of inlet-air temperature on performance of CFR engine using molten naphthalene as fuel. Compression ratio, 8; engine speed, 2000 rpm; spark advance, 22° B.T.C.

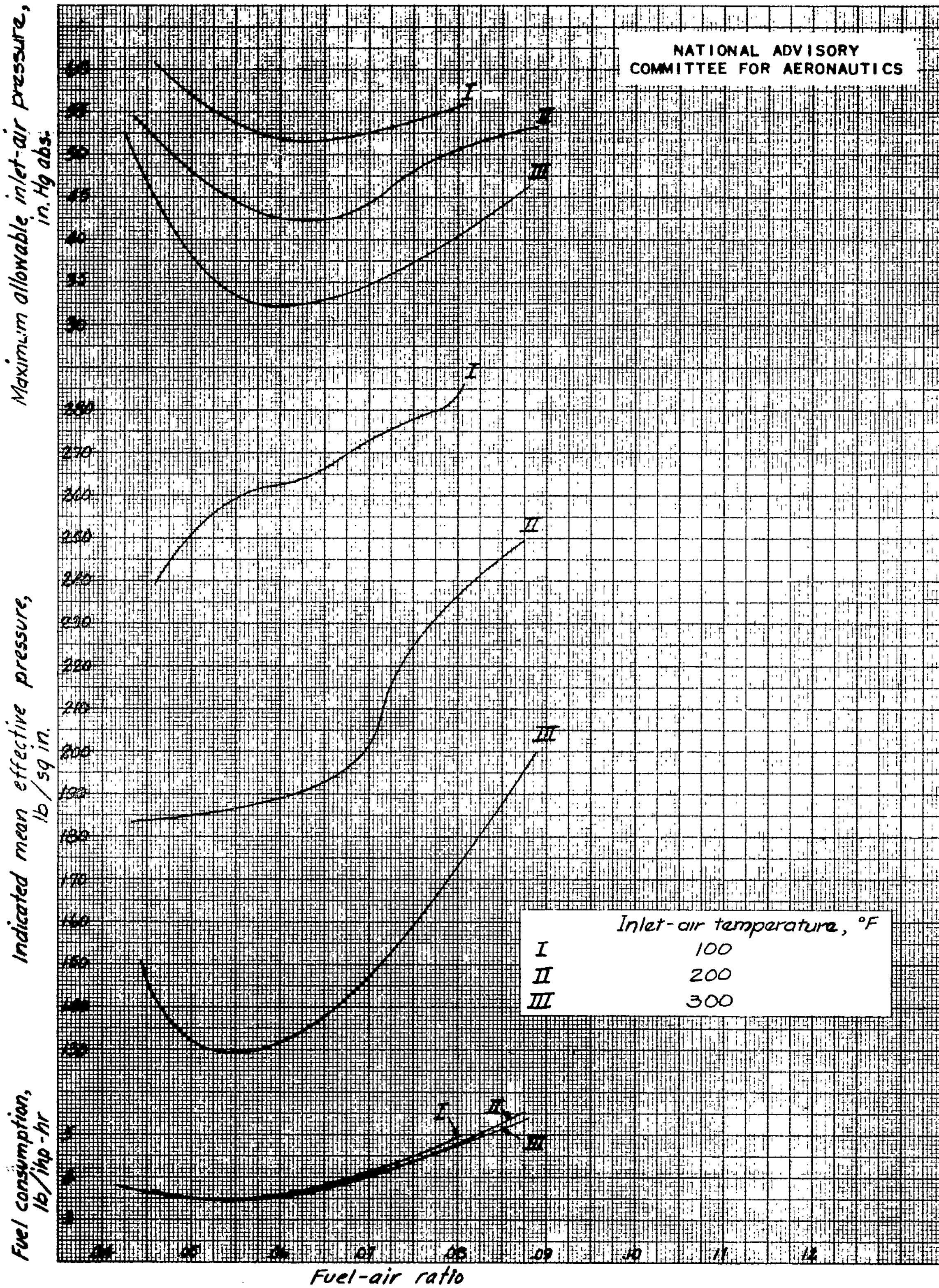

Figure 9. - Effect of inlet-air temperature on knock-limited performance of CFR engine using S-1 plus 6 ml TEL per gallon as fuel. Compression ratio, 8; engine speed, 2000 rpm; spark advance, 26° B.T.C.

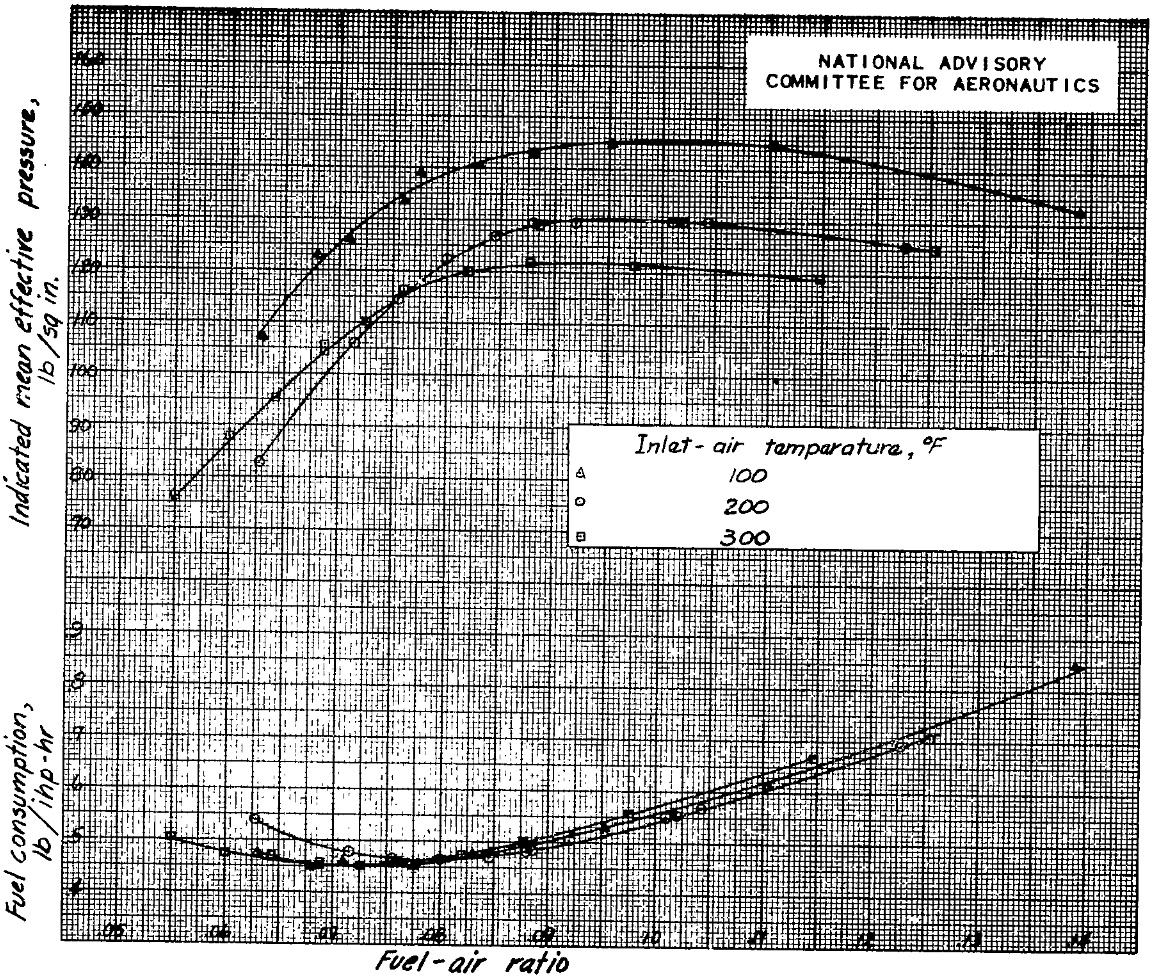

Figure 10. - Effect of inlet-air temperature on performance of CFR engine using molten naphthalene as fuel. Inlet-air pressure, 30.1 inches mercury absolute; compression ratio, 8; engine speed, 2000 rpm; spark advance, 22° B.T.C.

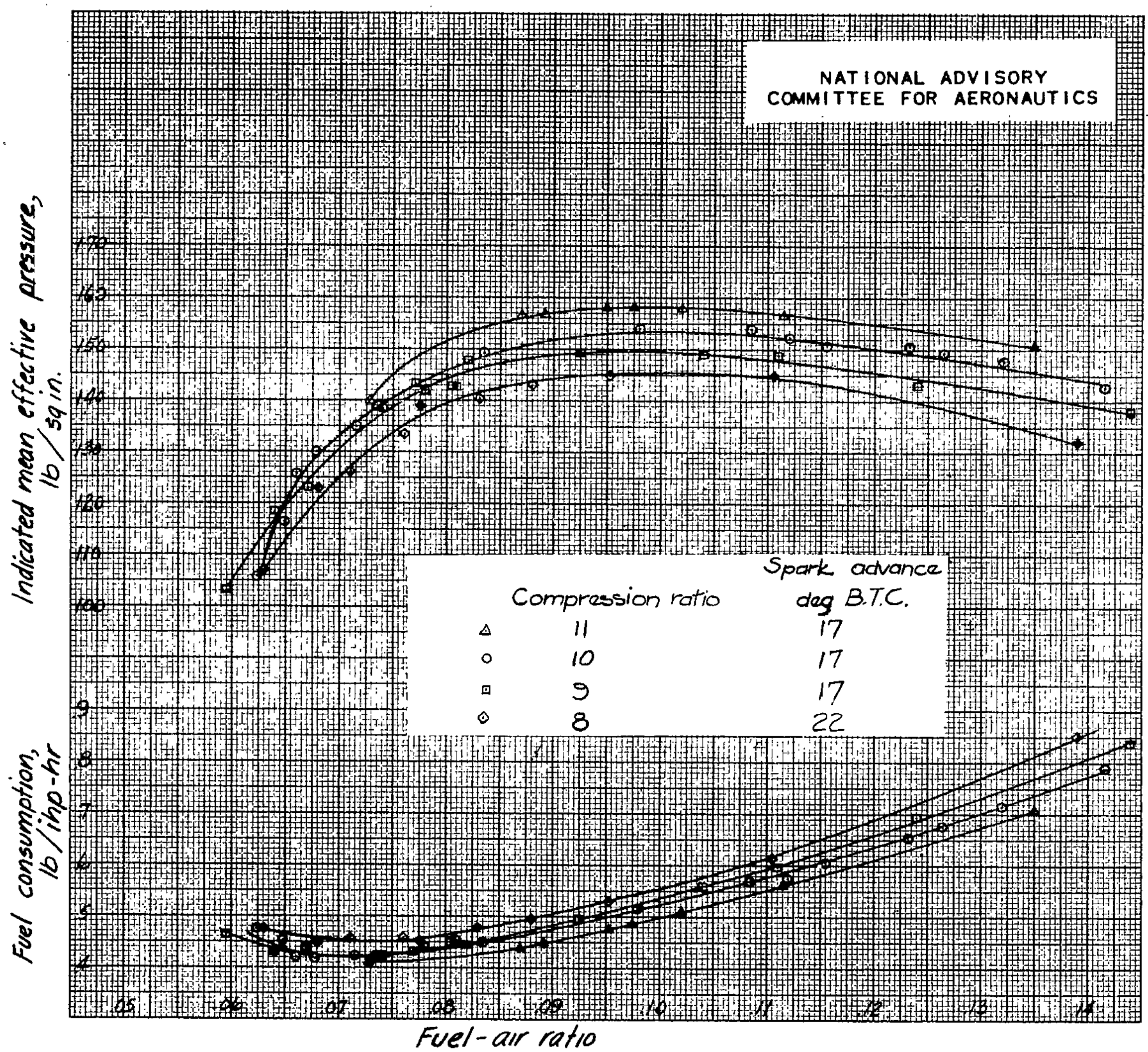

Figure 11. - Effect of compression ratio on performance of CFR engine using molten naphthalene as fuel. Inlet-air pressure, 30.1 inches mercury absolute; inlet-air temperature, 100° F; engine speed, 2000 rpm.

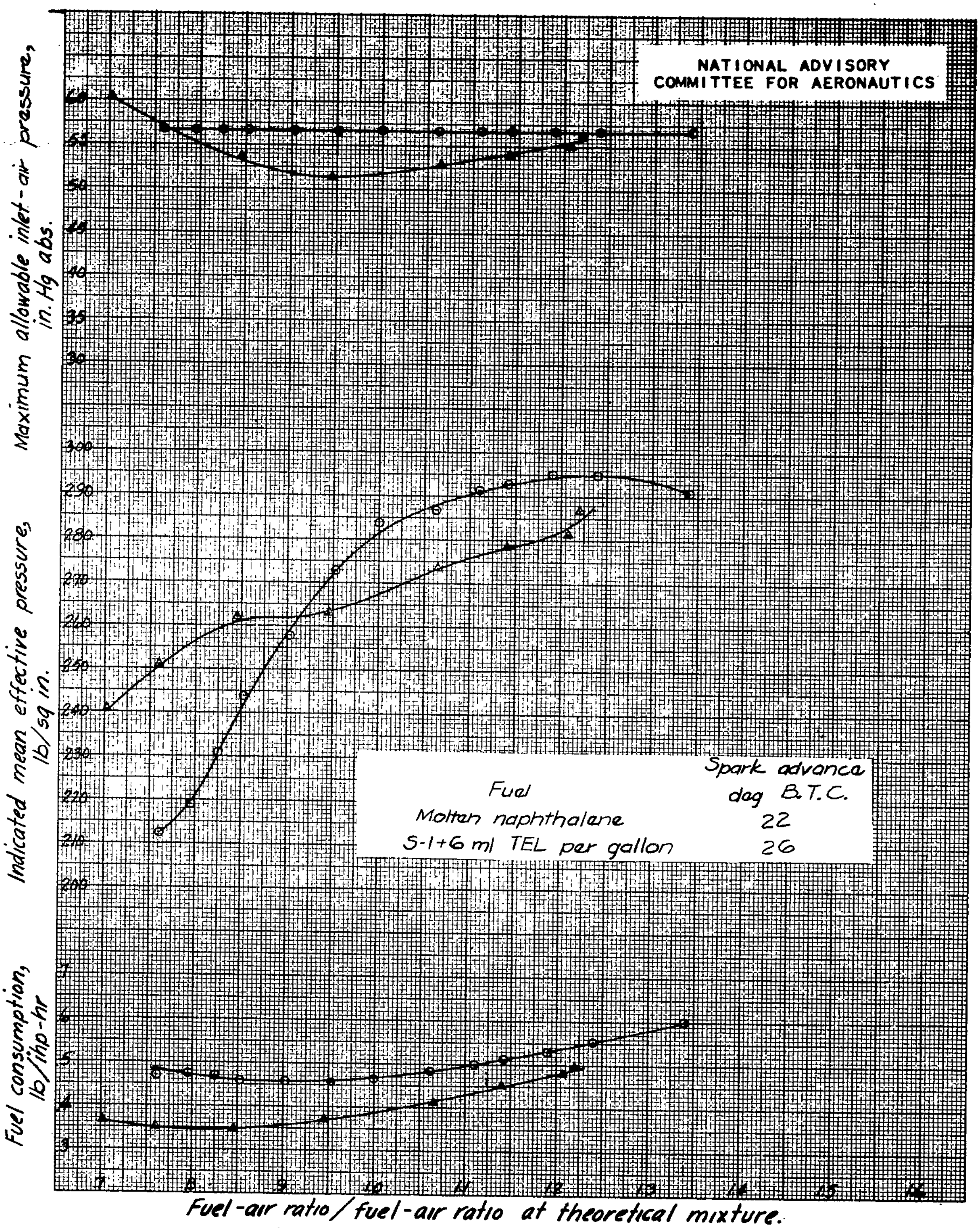

Figure 12. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 100° F; compression ratio, 8; engine speed, 2000 rpm; maximum inlet-air pressure available during naphthalene tests, 56.75 inches mercury absolute.

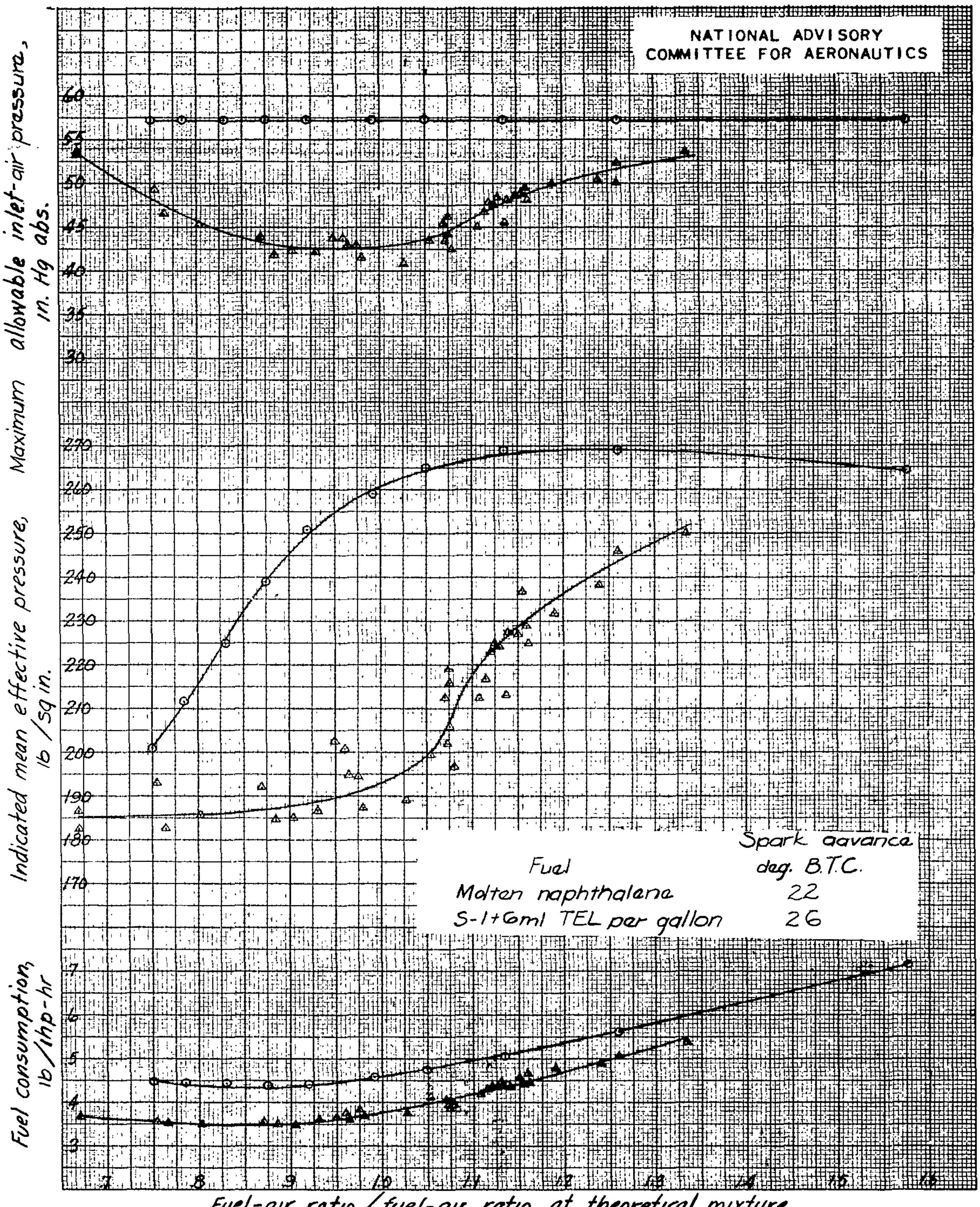

Figure 13. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 200° F; compression ratio, 8; engine speed, 2000 rpm; maximum inlet-air pressure available during naphthalene tests, 57.2 inches mercury absolute.

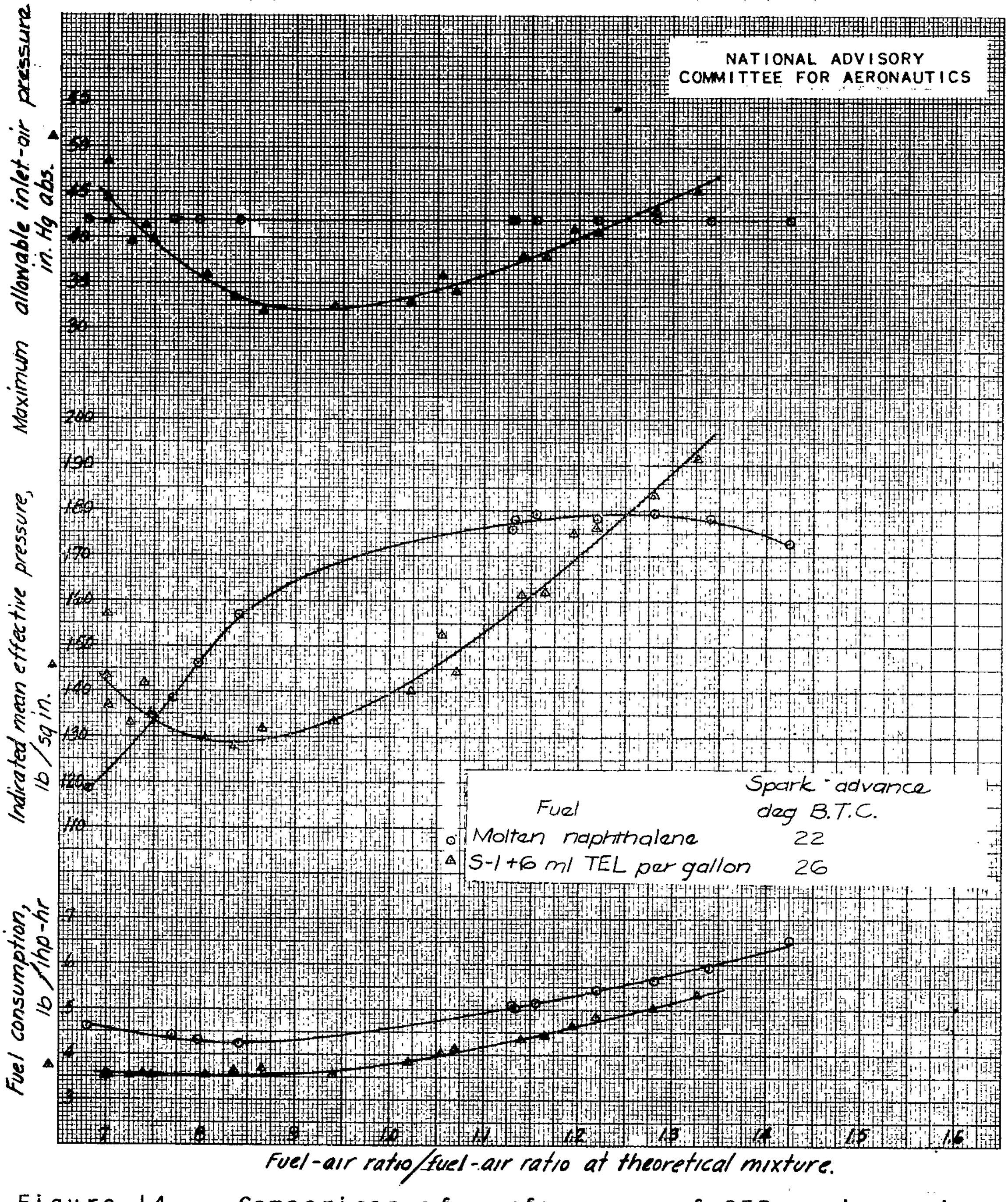

Figure 14. - Comparison of performance of CFR engine using molten naphthalene and S-1 plus 6 ml TEL per gallon as fuels. Inlet-air temperature, 200° F; compression ratio, 8; engine speed, 2000 rpm; maximum safe inlet-air pressure during naphthalene tests, 42.0 inches mercury absolute.

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ABSTRACT

Solid naphthalene was melted and used as fuel in modified CFR variable compression engine at 2000 rpm. Tests were made of compression ratio of 8 and inlet-air temperatures of 100°, 200° and 300°F. Performance was compared to that of S-1 isooctane with octane rating of almost 100. Results show that naphthalene has higher knock limit and is capable of higher IMEP than S-1. Naphthalene fuel consumption is higher than S-1 because of lower heating value, especially in lean mixture region. At low operating temperatures solid separation may clog oil lines.

NOTE: Requests for copies of this report must be addressed to: N.A.C.A., Washington, D. C.